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PHOTOSYNTHETIC COMPONENT OF ISOLATED
ECOLOGICAL CYCLES FOR SPACE TRAVEL

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THE USE OF VEGETABLE CULTURES AS THE PHOTOSYNTHETIC COMPONENT OF ISOLATED ECOLOGICAL CYCLES FOR SPACE TRAVEL

Man's exploration of space will be limited by his physiological requirements. Although dehydrated foods and tanked water and oxygen will suffice for space flights of relatively short duration, long-term operations will be possible only if these necessities can be derived from the environment within the space vehicle. Conservation of environmental mass will make mandatory some type of closed ecological system kept in operation by a source of continuous energy. Conceivably, such a system will involve a carbon-dioxide exchange between humans and plants, waste reutilization, and the growth of plants for human consumption. Items on the original inventory will be used again and again for the continued sustenance of man.

Several sustenance systems have been proposed ^{1,2,3}. In each case, attention was centered on the use of algae as the photosynthetic component of the closed cycle. Algae, because of their microscopic size, lend themselves to manipulation under conditions that promote the greatest photosynthetic efficiency. Also, unlike the higher plants where a portion of the plant structure ordinarily is not eaten, algae are represented as being 100 per cent edible. Consequently, only algae have been seriously considered for use as a photosynthetic agent.

A factor exists which may limit or even preclude such a use for algae. Algae has been used as a dietary supplement,^{4,5} but no instance has been reported where the diet of man, or any other terrestrial mammal, has consisted entirely of algae. It is safe to assume that algae will require elaborate preparation to make the cells palatable to humans.

In contrast, higher plants have long been a primary source of human food material. Many people exist entirely on vegetable diets, the preparations of which require only cleaning and cooking. Moreover, the growth of some higher plants in soilless culture under partially controlled conditions is already accepted commercial practice ^{6,7,8,9}.

For these reasons, it appeared desirable to make a study of the use of higher plants as the photosynthate in the human sustenance system. The present paper discusses the results of such a study. It is hoped that the information will provide additional insight to the magnitude and the complexity of the problem of sustaining human life in an extra-terrestrial environment.

Nutrient Requirements

Food is used to furnish heat and mechanical energy, build and repair tissues, and regulate body processes. Energy requirements are met by the intake of carbohydrate, protein, and fat in quantity sufficient to furnish a specific number of calories. The other requirements, however, are complex and imperfectly understood. Nutritional health is conveniently maintained by eating a wide variety of food materials, both of plant and animal origin. Such practice makes unnecessary a close surveillance of the nutritional components of the diet. Where variety is limited, a careful check must be made of the detailed dietary needs and measures taken to satisfy such needs in the daily diet.

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The daily essential amino acid, vitamin, and mineral requirements of the adult male are listed in Table I. Many vitamin and mineral requirements are yet undetermined. Until recently, amino acid requirements were stated in terms of a minimum daily intake of 60 to 65 grams of proteins, the proteins being from both animal and plant sources. Now, the individual essential amino acid requirements have been established ¹⁰. The minimal nitrogenous needs of man for the synthesis of the nonessential acids are met by consuming about 16 grams of protein ¹¹. This information provides a more precise basis on which diets can be devised.

Vegetable Diets

Nitrogen is a key element in the tissue structure of the human body. Unlike carbon, hydrogen, and oxygen which can be furnished by either carbohydrates, proteins or fats, nitrogen is present only in the amino acids constituting proteins. It is convenient, therefore, to orient a diet toward a protein food of satisfactory quality.

Of all human foods of plant origin, the peanuts, the legumes and the cereal grains are the richest in protein. None of the cereal grains can be planted closer in soilless culture than in agriculture ¹². Consequently, only the peanut, and one protein-rich legume, the lima bean, were considered as primary sources of protein.

Eight diets were devised. Four are oriented toward the peanut proteins and four toward the proteins of the lima bean. Each diet will furnish a daily intake of 2800 to 3000 kilocalories, energy sufficient to sustain a young male performing light duties ¹³. The diets along with their mineral and vitamin content are presented in Figures 1 and 2. ¹⁴ Only the more critical minerals and vitamins are considered. With the exception of sodium and chlorine, the other mineral requirements will be met in plant foods, provided that sufficient quantities of these elements are included in the root environment. Sodium and chloride ions are important in animal physiology but are almost totally absent in plant tissue. It appears that from a mineral and vitamin standpoint, Peanut Oriented Diets #3 and #4 and all four of the lima bean oriented diets would prove satisfactory.

The essential amino acid composition of each of the eight diets is listed in Table II. ¹⁵ With the exception of Lima Bean Oriented Diet #1, all diets are deficient in the sulfur-containing amino acid, methionine. Such a deficiency is common in vegetable diets. It has been reported, however, that another sulfur-containing amino acid, cystine, can replace about 80 per cent of the minimum methionine need. ¹⁶ Figure 3 shows the total methionine-cystine content of the diets in terms of per cent of daily requirement. Assuming a sparing effect of cystine on the methionine requirement, the proteins in all the diets are of satisfactory quality.

Food bulk and the relative proportions of protein, fat, and carbohydrate, while not critical nutritionally, are important in a psychological sense. Diets varying too greatly in these respects from diets normally eaten could be a source of continual dissatisfaction and discomfort. In Figures 4 and 5 these factors are compared with the recommended daily consumption ^{14, 17}. Three of the eight diets, the Peanut Oriented Diet #4 and the Lima Bean Oriented Diets #3 and #4, have relative compositions approaching that of the recommended diet.

Oxygen Production

Man in his isolated environment will be dependent upon the photosynthetic component of the system not only for food but oxygen as well. The daily oxygen requirement of a male feeding on a diet providing an energy intake of 2800 to 3000 kilocalories has been shown to be approximately 1.7 pounds.^{3,18} A comparison of the oxygen requirement with the quantity of oxygen produced in growing the crops from which the eight diets would be derived is made in Figure 6. The oxygen produced over and above the human requirement can be shown to be equal to the amount needed to stabilize the plant refuse by conversion to inorganic compounds.

Vegetable Culture Systems

Figure 7 is a schematic diagram of a human sustenance system in which a vegetable culture is employed as the photosynthetic component. The other components of the system have been discussed elsewhere ³.

Three methods of soilless culture have been developed for the large scale production of vegetable crops: the "water culture" or "hydroponic" method, the "sand culture" method, and the "subirrigation" or "gravel culture" method. From the standpoint of nutrition control and maintaining aerobiosis at the plant root system, the subirrigation or gravel culture method is superior to the other two methods and has largely replaced them in commercial vegetable growing.

Figure 8 is a diagram of a subirrigation type of system. Plants are grown in shallow beds of gravel (6 to 8 inches deep), into which a nutrient solution is pumped two to three times a day. The application of the nutrient solution is brief, time being allowed only for the formation of a wet film on the surface of the gravel. The entire cycle of filling and withdrawal requires but a few minutes. The root system penetrates the bed, taking moisture and nutrients from the wet surfaces. Gravel particles of one-half inch and less are generally employed. Information concerning details of construction is available ⁷. The total weight of the system would be reduced considerably by the use of plastic tanks filled with small plastic particles having a specific gravity only slightly greater than that of the nutrient solution.

The function of the nutrient solution is to supply water, oxygen and the essential mineral nutrients in the proper proportions to the plant roots. Information is available from several sources relating to nutrient requirements of plants and how they are met in soilless culture ^{7,19,20,21}. The essential macronutrients are: nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium. Table III gives the ionic form in which these elements are generally employed in nutriculture, along with the concentrations in typical nutriculture solutions. It will be noted that nitrogen can be utilized either in the form of nitrate or the ammonium ion. Also, a point should be made of the fact that, unlike animals which have a major sodium and chloride requirement (see Table I), plants require little if any of these ions. Instead, plants must have for their nutrition the potassium and sulfate ions.

Certain other elements, the micronutrients, are needed in plant nutrition, but not in concentrations required of the macronutrients. The micronutrients are: iron, manganese, boron, copper, zinc and molybdenum. Although they are required in very low concentrations (less than 1 milligram per liter),

they become toxic at high concentrations ⁷. Plants frequently absorb substantial quantities of sodium and chloride ions. These ions are not required for plant growth, however, and their presence in excess can interfere with the osmotic balance of the system.

The osmotic pressure of the nutrient solution should be between 0.5 to 2.0 atmospheres. Within this range of pressure, the actual quantities of ions present in the solution are not as important as the ratio between them. The tolerance range for pH is from 4 to 8, the optimum falling at 6 to 6.5. The temperature of the root environment should not fall under 50° F or greater than 100° F. Most plants appear to require at least 1000 foot-candles of light to support growth. Higher levels improve growth - up to 6,000 to 10,000 foot-candles, depending upon the plant. No substantial evidence exists that, at concentrations normally present in air (0.03 per cent by volume), carbon dioxide is a limiting factor. Inhibition by carbon dioxide apparently does not occur at concentrations less than 15 to 20 per cent ²⁰.

A water and mineral balance across the vegetable culture system is presented in Table IV. The column numbers correspond to the numbers in parentheses in Figure 7. The balance was struck for a nutrient solution similar in composition to that given in Table III for "Ohio State" and with a maximum chloride concentration of 350 milligrams per liter ²⁰. The balance establishes the volumes and concentrations of the culture system as well as the daily addition to and the daily withdrawal from the system. The quantity of ions supplied to the system each day by the wastes stabilizer is equal to that quantity taken out of the system as the result of harvesting and the withdrawal of salt solution.

Space and Weight Requirements

Little data is to be found on crop yields in soilless culture. In general, such culture produces 4 to 10 times the average yield in soil culture. Based on the information available, ²¹ the area, cubage, and weight requirements of the vegetable culture system were estimated for each of the eight diets. See Figure 9. It is to be noted that with the exception of Lima Bean Oriented Diet #4, the diets offering the greatest variety have the least spacial and weight requirements. This is due to the fact that, in general, the growth of carbohydrate-rich vegetables require less area than does the growth of vegetables rich in protein. The spacial requirements of growing corn, like all field crops, are relatively large. As a result, Lima Bean Oriented Diet #4 is out of proportion with the other diets.

It is interesting to compare the cubage requirements for a vegetable culture system with those reported for systems in which algae is used as a photosynthate. Myers¹⁸ and Rich³ have estimated the cubage of a system employing *Chlorella pyrenoidosa* to be about 80 cubic feet per man-unit. Burk et al²² describe a system in which a thermophilic strain of *Chlorella* with a high growth rate is used as the photosynthetic agent. They estimate the cubage of the system to be 5 cubic feet per man-unit. These values are to be compared with the 7000 cubic feet needed to furnish a man with a balanced vegetable diet. Obviously, the spacial requirements of a vegetable culture system are such as to preclude its use in space vehicles.

On the other hand, a vegetable system is of a size that would permit its use in a semi-permanent installation such as a large earth satellite or a lunar

base. The special requirements might be reduced, somewhat, through a cropping which is closer than that ordinarily practiced in soilless gardening or by the use of hormones or hormone-stimulating preparations in plant nutrition. Forcing procedures such as continual illumination would be effective toward this end. A greater reduction would be realized if both algal and vegetable cultures were used in the same sustenance system. Protein-rich algae could be supplemented with carbohydrate-rich vegetables, such as potatoes, to reduce the total special requirements to a fraction of that needed for an all-vegetable diet.

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Table I

DAILY ESSENTIAL AMINO ACID, VITAMIN, AND
MINERAL REQUIREMENTS OF AN ADULT MALE

Essential Amino Acids*		Vitamins**		Major Minerals**		Trace Minerals**
Tryptophan	0.50 g	A	5,000 I.U.	Calcium	0.78 g	Cobalt
Phenylalanine	2.20 g	D	?	Chlorine	6.04 g	Manganese
Lysine	1.60 g	E	?	Sodium	3.90 g	Molybdenum
Threonine	1.00 g	K	?	Phosphorus	1.17 g	Zinc
Methionine	2.20 g	Ascorbic Acid	71.6 mg	Potassium	?	
Leucine	2.20 g	Thiamine	1.62 mg	Magnesium	?	
Isoleucine	1.40 g	Riboflavin	1.62 mg	Sulfur	-	
Valine	1.60 g	Niacin	16.2 mg	Iron	11.7 mg	
		Pyridoxine group	2.0 mg	Copper	1.17mg	
		Pantothenic acid	?	Iodine	0.26mg	
		Folic acid group	?			
		Biotin	?			
		Inositol	?			
		B ₁₂	?			

* Rose, W. C. et al. "The Amino Acid Requirements of Man. 15. The Valine Requirement; Summary and Final Observations." J. Biol. Chem., 217, 987. 1955.

** Handbook of Biological Data. WADC 56-273, p. 196. 1956.

Table II

ESSENTIAL AMINO ACID CONTENT OF PEANUT AND LIMA BEAN ORIENTED DIETS
FURNISHING A DAILY ENERGY INTAKE OF 2800 TO 3000 KILOCALORIES,
EXPRESSED IN TERMS OF PER CENT DAILY REQUIREMENT.

Essential Amino Acids	Diets							
	Peanut Oriented				Lima Bean Oriented			
	#1	#2	#3	#4	#1	#2	#3	#4
Isoleucine	535	550	550	386	1340	620	632	650
Leucine	490	510	510	336	820	386	445	537
Lysine	290	312	312	275	850	405	448	462
Methionine	70	74	74	59	104	58	71	83
Phenylalanine	360	368	368	222	454	230	289	310
Threonine	430	450	450	360	1000	490	530	572
Tryptophan	200	214	214	178	456	254	260	280
Valine	425	443	443	344	750	388	455	490

Table III

MACRO-ION CONCENTRATION OF TYPICAL NUTRIENT SOLUTIONS.*

Nutrient Solution*	NO ₃ ⁻ mg/l	PO ₄ ³⁻ mg/l	SO ₄ ²⁻ mg/l	Cl ⁻ mg/l	K ⁺ mg/l	Mg ⁺⁺ mg/l	Ca ⁺⁺ mg/l	NH ₄ ⁺ mg/l
Lago	434	93	1008	0	273	72	360	0
Shell	434	124	864	0	273	48	360	0
Ohio State	428	87	1018	0	269	53	356	32
Purdue	310	31	576	178	390	24	180	36
California	868	31	192	0	234	48	160	18
New Jersey	558	71	288	0	90	55	180	25

* Ellis, C. and Swaney, M. W. Soilless Growth of Plants. 2nd ed. Reinhold Publishing Corp. 1947.

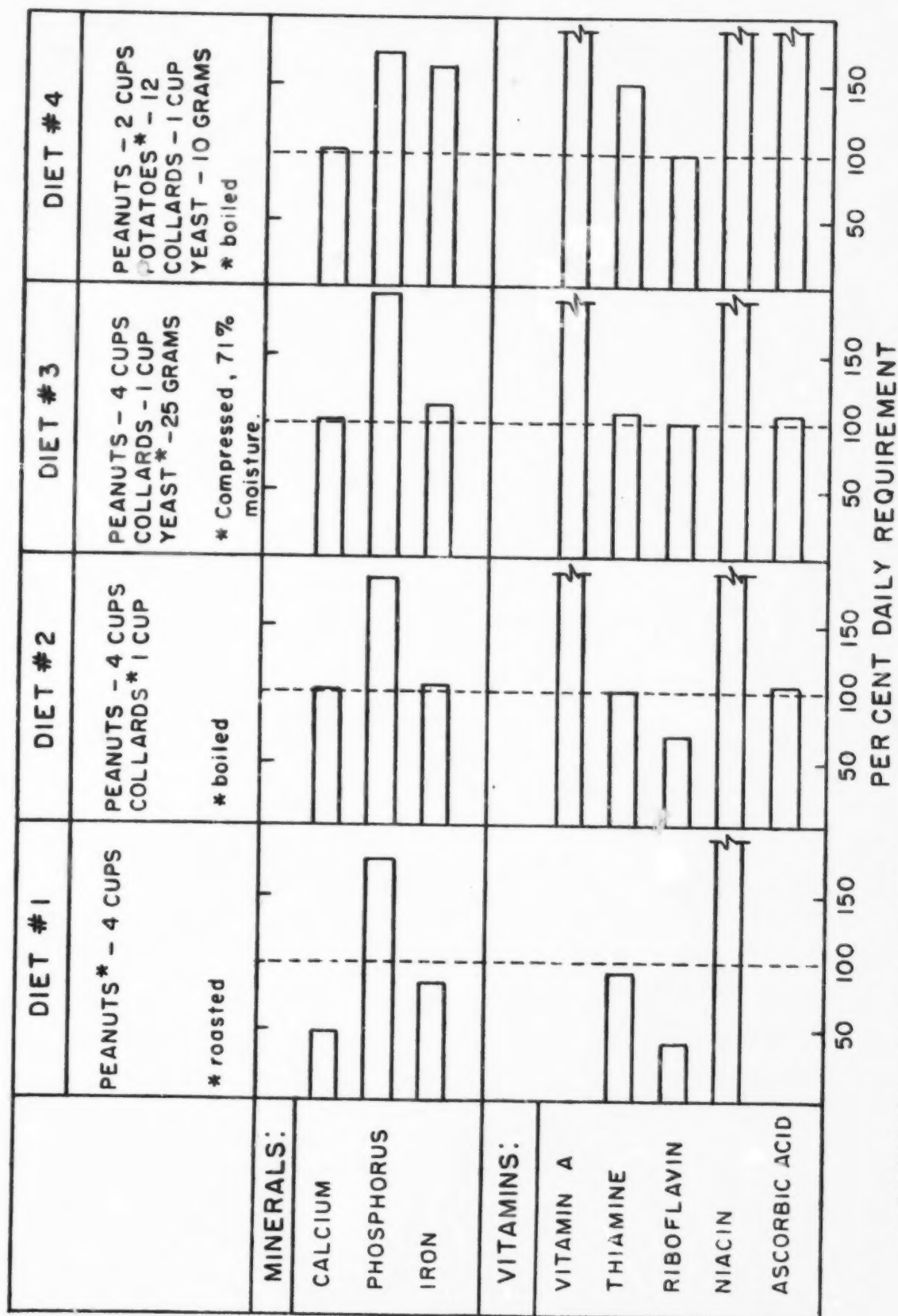
Table IV

WATER AND MINERAL BALANCE ACROSS VEGETABLE CULTURE SYSTEM.
BASIS: ONE MAN-UNIT-DAY FEEDING ON PEANUT DIET #1. (POUNDS)

	#1 Vegetable Culture System	#2 Salt Solution	#3 Harvest	#4 Nutrient Solution	#5 Transpira- tion and Evaporation
Water	29,600	38	9,000	10,618	1580
Ions					
K ⁺	7.95	10.3 x 10 ⁻³	87.5 x 10 ⁻³	97.8 x 10 ⁻³	0
Ca ⁺⁺	10.50	13.7 x 10 ⁻³	43.5 x 10 ⁻³	57.2 x 10 ⁻³	0
Mg ⁺⁺	1.56	2.0 x 10 ⁻³	18.9 x 10 ⁻³	20.9 x 10 ⁻³	0
NH ₄ ⁺	3.62	4.7 x 10 ⁻³	192.0 x 10 ^{-3*}	196.7 x 10 ⁻³	0
Na ⁺	7.50	9.75 x 10 ⁻³	0**	9.75 x 10 ⁻³	0
Cl ⁻	10.30	13.4 x 10 ⁻³	0**	13.4 x 10 ⁻³	0
PO ₄ ⁼	2.34	3.04 x 10 ⁻³	17.00 x 10 ⁻³	20.04 x 10 ⁻³	0
SO ₄ ⁼	47.80	62.2 x 10 ⁻³	12.00 x 10 ⁻³	74.20 x 10 ⁻³	

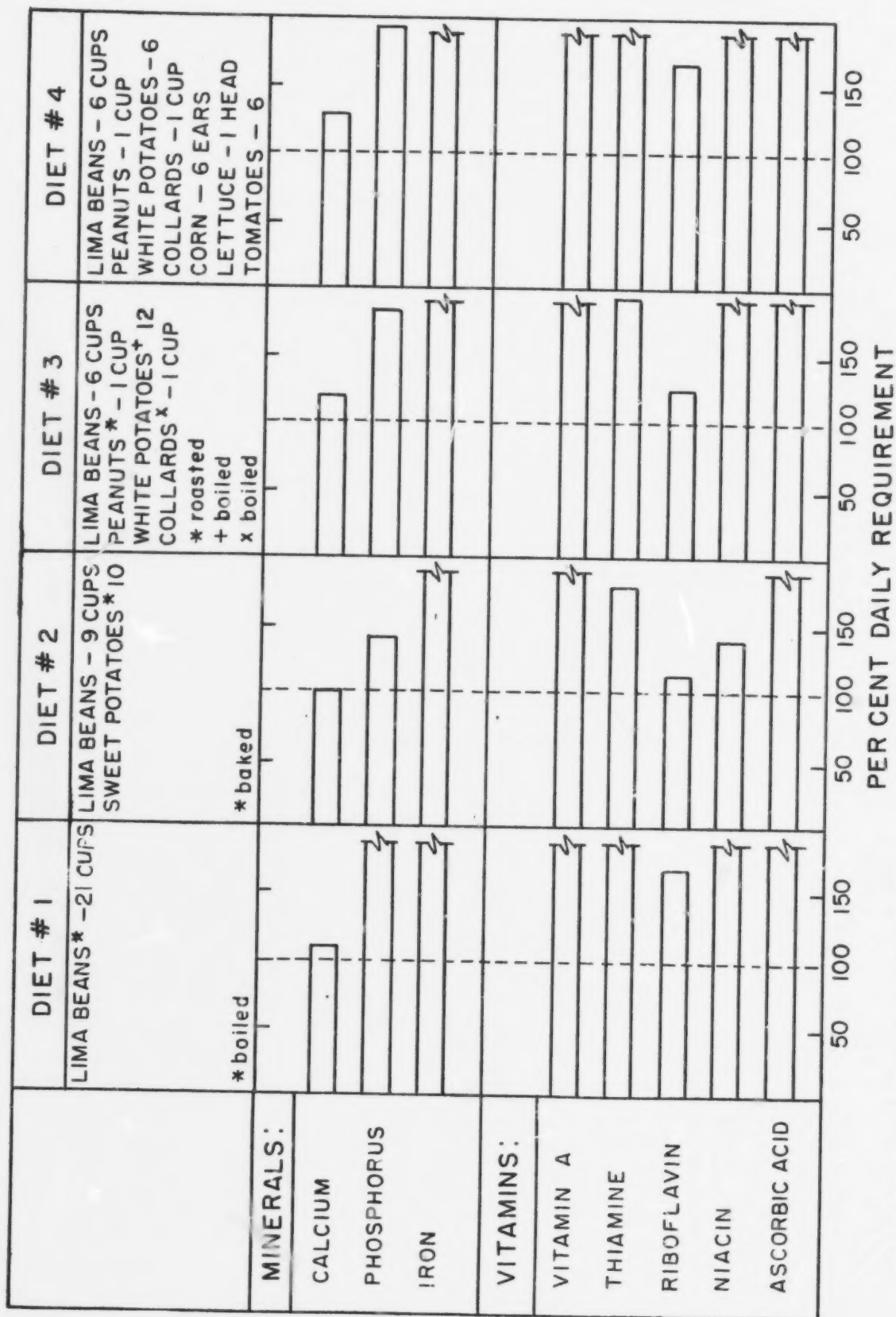
* Expressing protein nitrogen as NH₄⁺.

** Assumed.



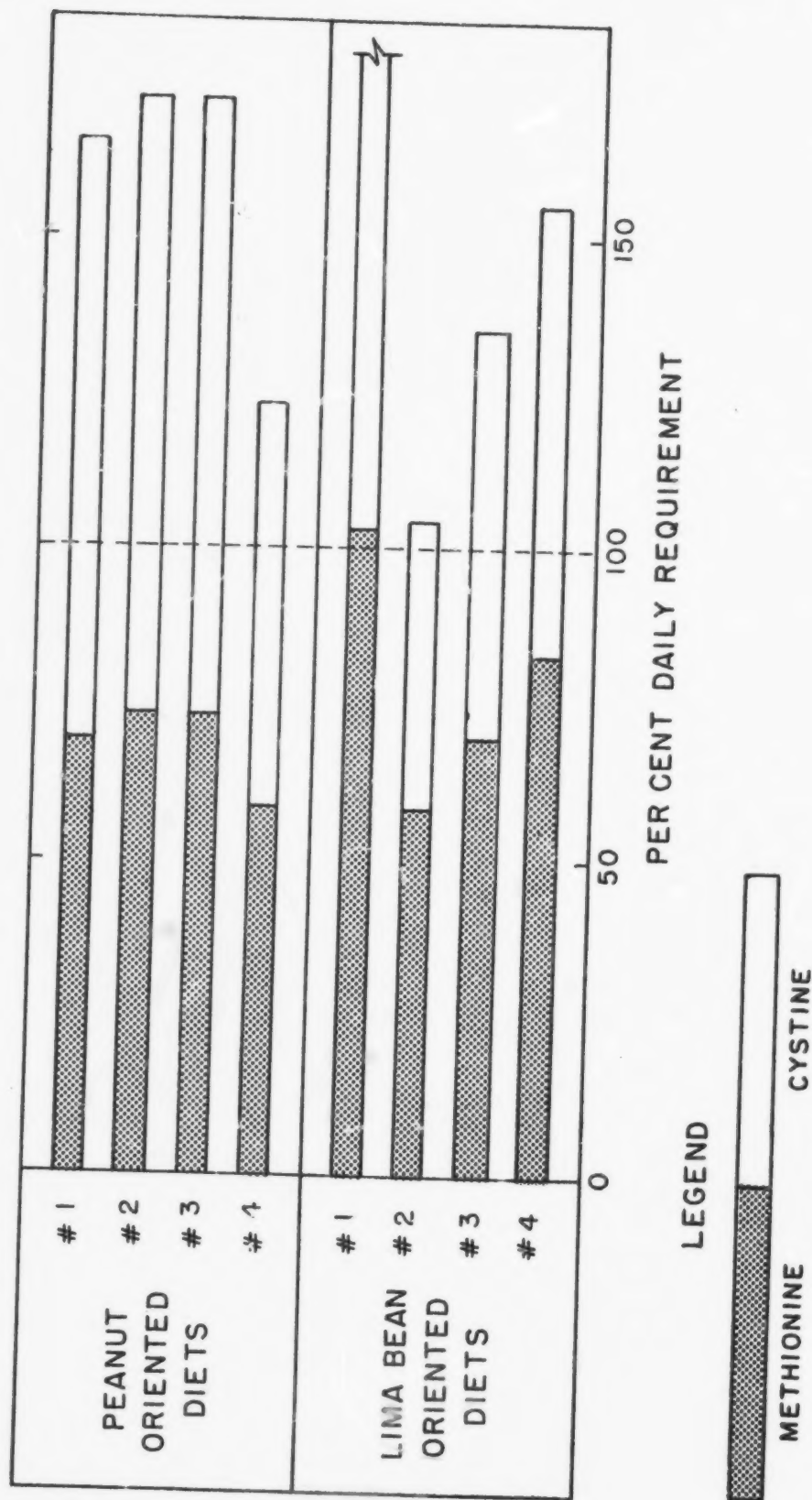
MINERAL AND VITAMIN CONTENT OF PEANUT ORIENTED DIETS
FURNISHING DAILY ENERGY INTAKE OF 2800 TO 3000 KILOCALORIES

FIGURE 1



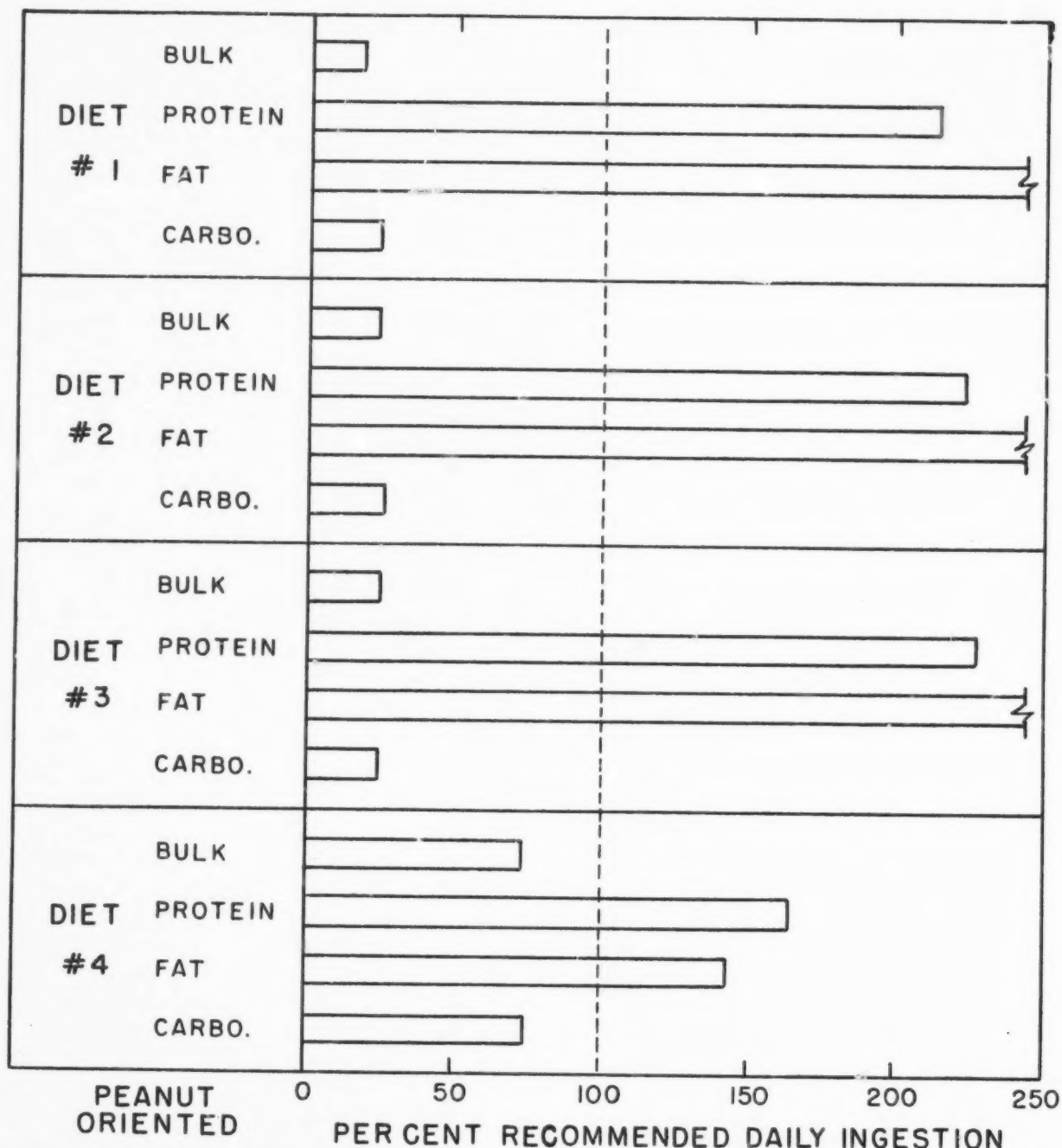
MINERAL AND VITAMIN CONTENT OF LIMA BEAN ORIENTED DIETS
FURNISHING DAILY ENERGY INTAKE OF 2800 TO 3000 KILOCALORIES

FIGURE 2



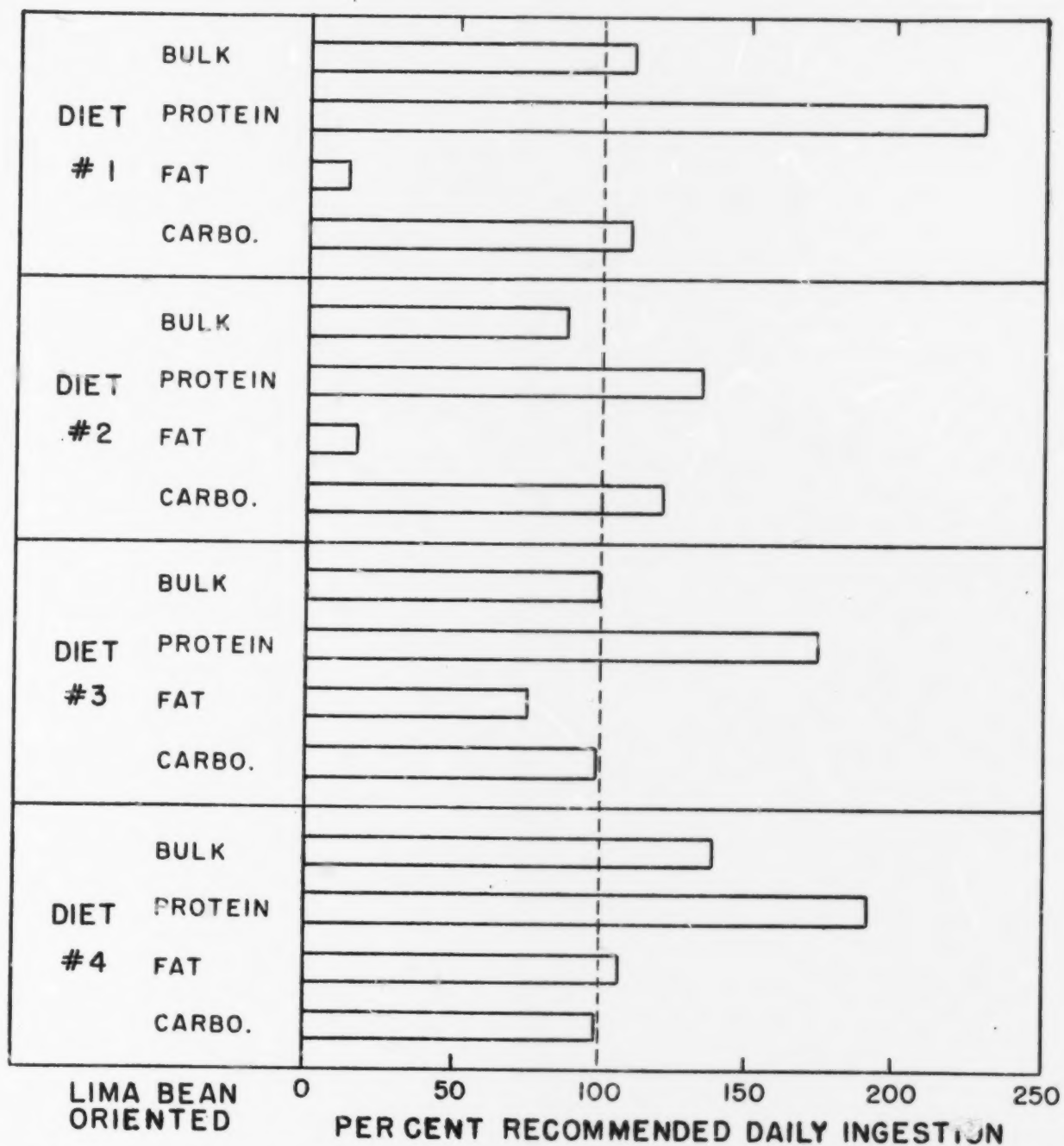
METHIONINE AND CYSTINE CONTENT OF PEANUT AND LIMA BEAN
ORIENTED DIETS FURNISHING DAILY ENERGY INTAKE OF
2800 TO 3000 KILOCALORIES

FIGURE 3



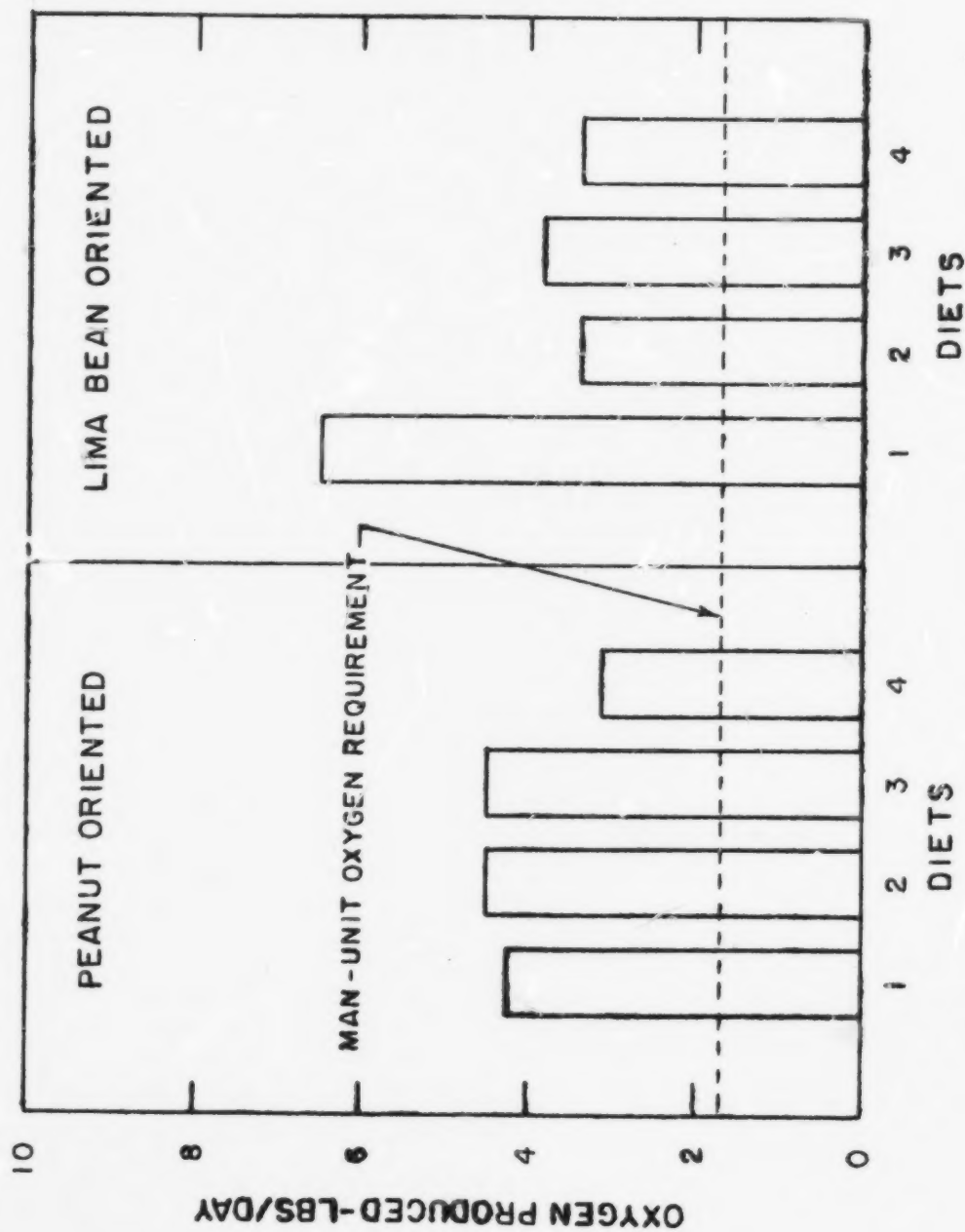
BULK, PROTEIN, FAT, AND CARBOHYDRATE CONTENT OF PEANUT ORIENTED DIETS FURNISHING DAILY ENERGY INTAKE OF 2800 TO 3000 KILOCALORIES

FIGURE 4



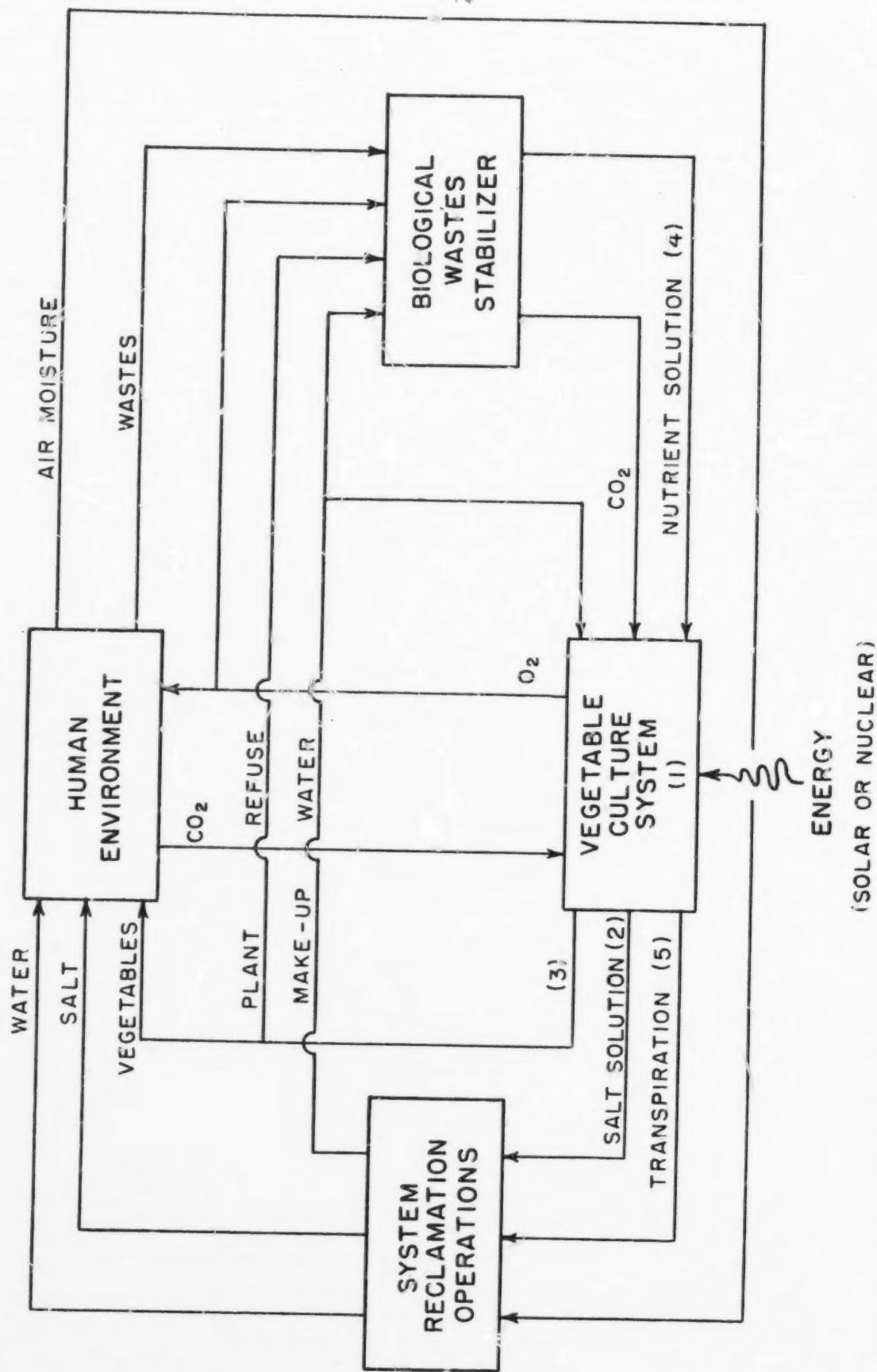
BULK, PROTEIN, FAT, AND CARBOHYDRATE CONTENT OF LIMA BEAN ORIENTED DIETS FURNISHING DAILY ENERGY INTAKE OF 2800 TO 3000 KILOCALORIES

FIGURE 5



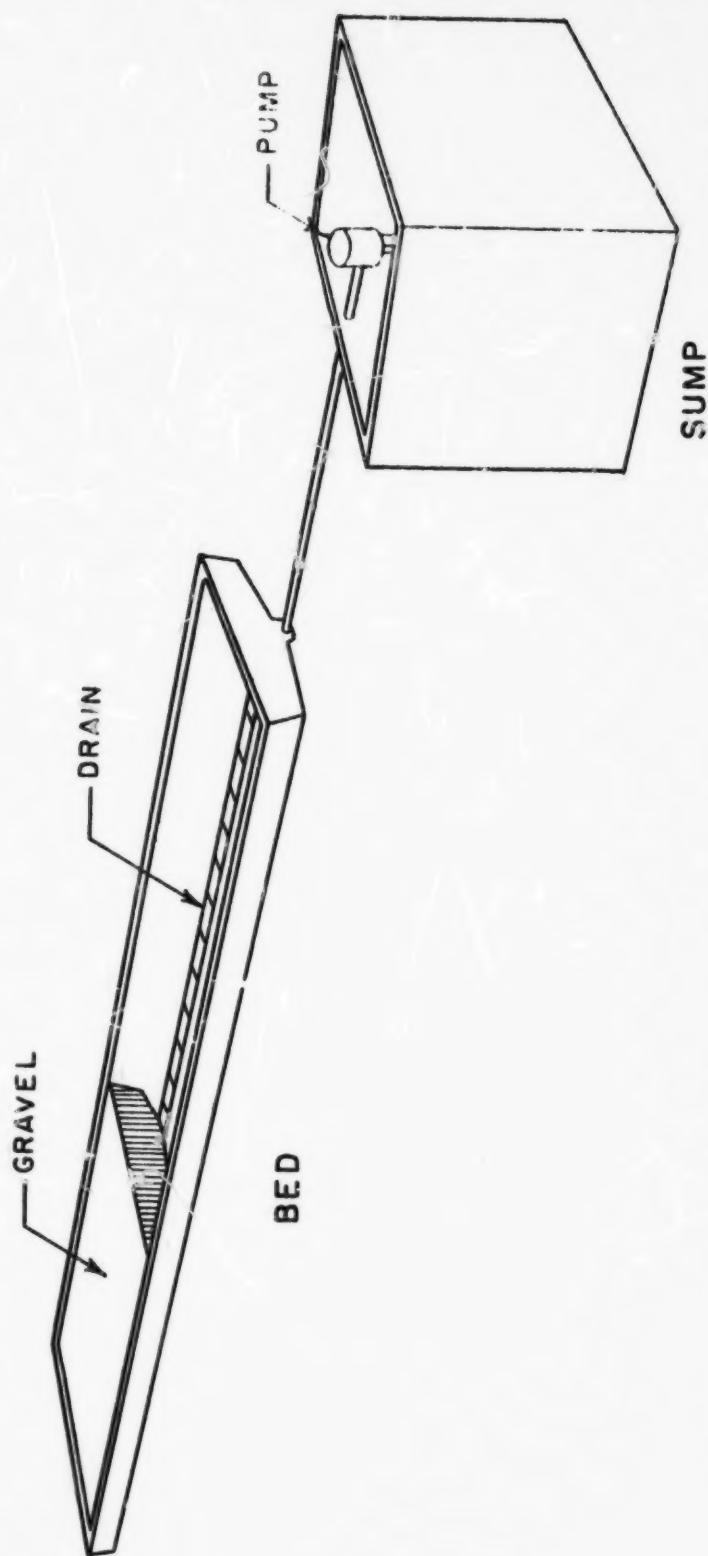
PHOTOSYNTHETIC ACTIVITY OF VEGETABLE
CULTURES IN TERMS OF DAILY OXYGEN PRODUCTION

FIGURE 6



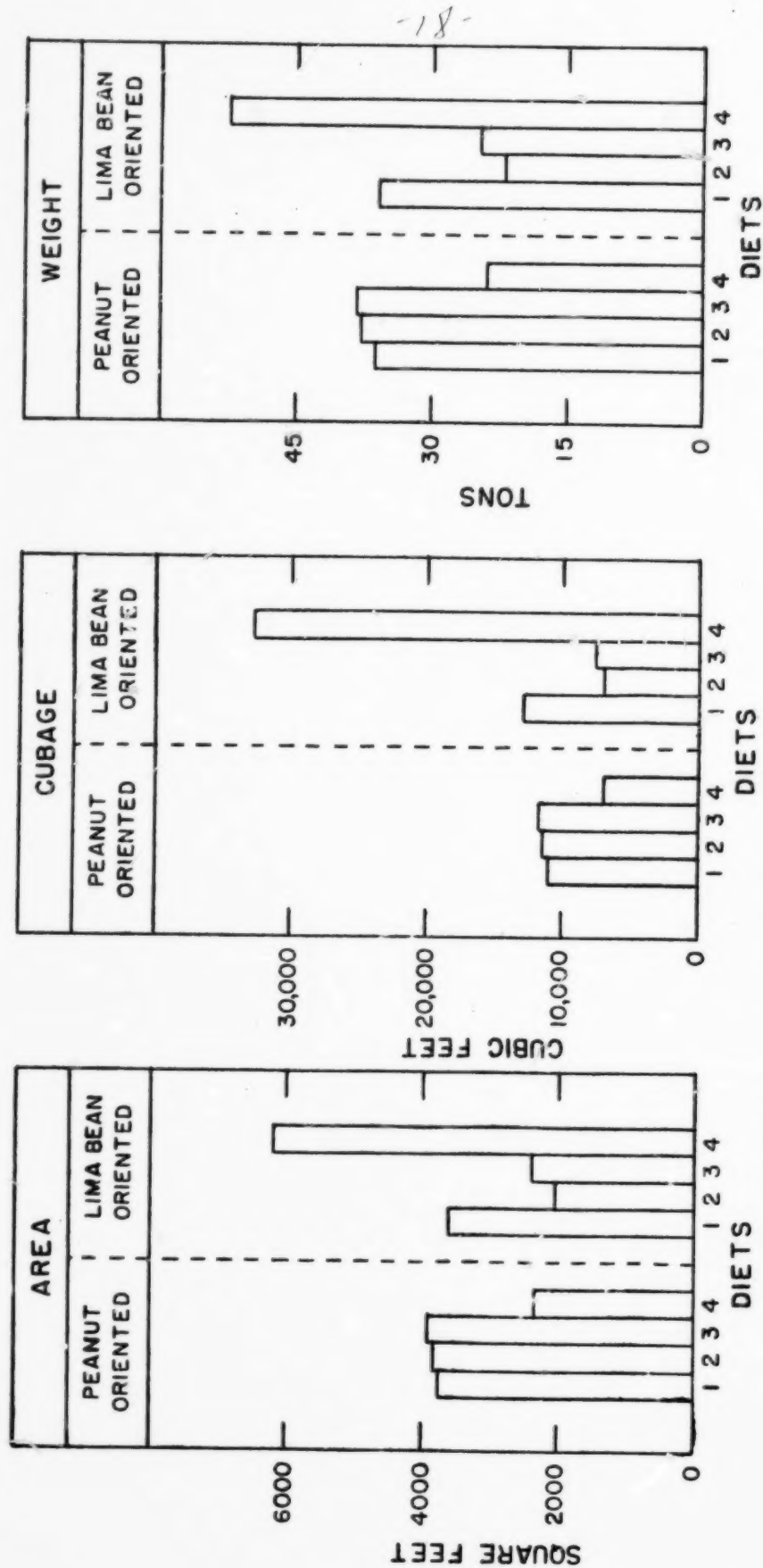
SCHEMATIC DIAGRAM OF A HUMAN SUSTENANCE SYSTEM IN WHICH A VEGETABLE CULTURE IS EMPLOYED AS THE PHOTOSYNTHETIC COMPONENT

FIGURE 7



SCHEMATIC DIAGRAM OF A SUBIRRIGATION OR GRAVEL TYPE
OF NUTRICATION SYSTEM

FIGURE 8



AREA, CUBAGE, AND WEIGHT REQUIREMENTS OF NUTRICULTURE
SYSTEMS PER MAN-UNIT

FIGURE 9